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Supplementary Materials for

Stabilization of fault slip by fluid injection in the laboratory and in situ

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Reference (*51*)

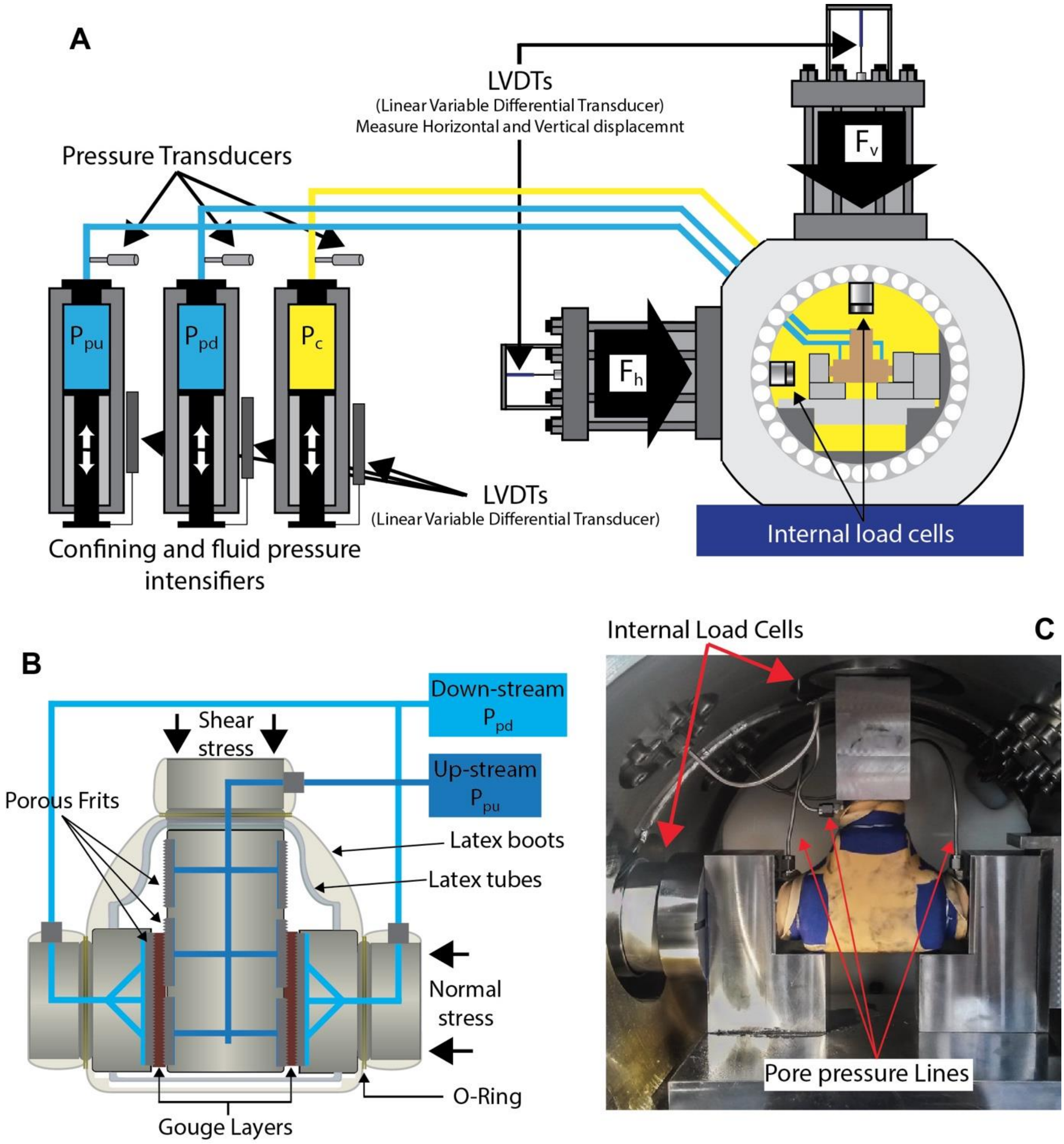

Fig. S1. Experimental configuration for fluid injection and fault slip in the laboratory (18**).** (**A**) BRAVA rock deformation apparatus (1) showing the double direct shear configuration with the pressure vessel and the intensifiers used to pressurize fluid and confining pressure. (**B**) Close-up view of the sample assembly in the double direct shear configuration for vessel experiments. (**C**) Initial set-up showing the jacketed sample assembly with the pore fluid pressure tubing and the internal load cells within the pressure vessel (Photo Credit: Marco Maria Scuderi, Dipartimento di Scienze della Terra, La Sapienza Università di Roma, Piaz. Aldo Moro 5, 00185 Rome, Italy).

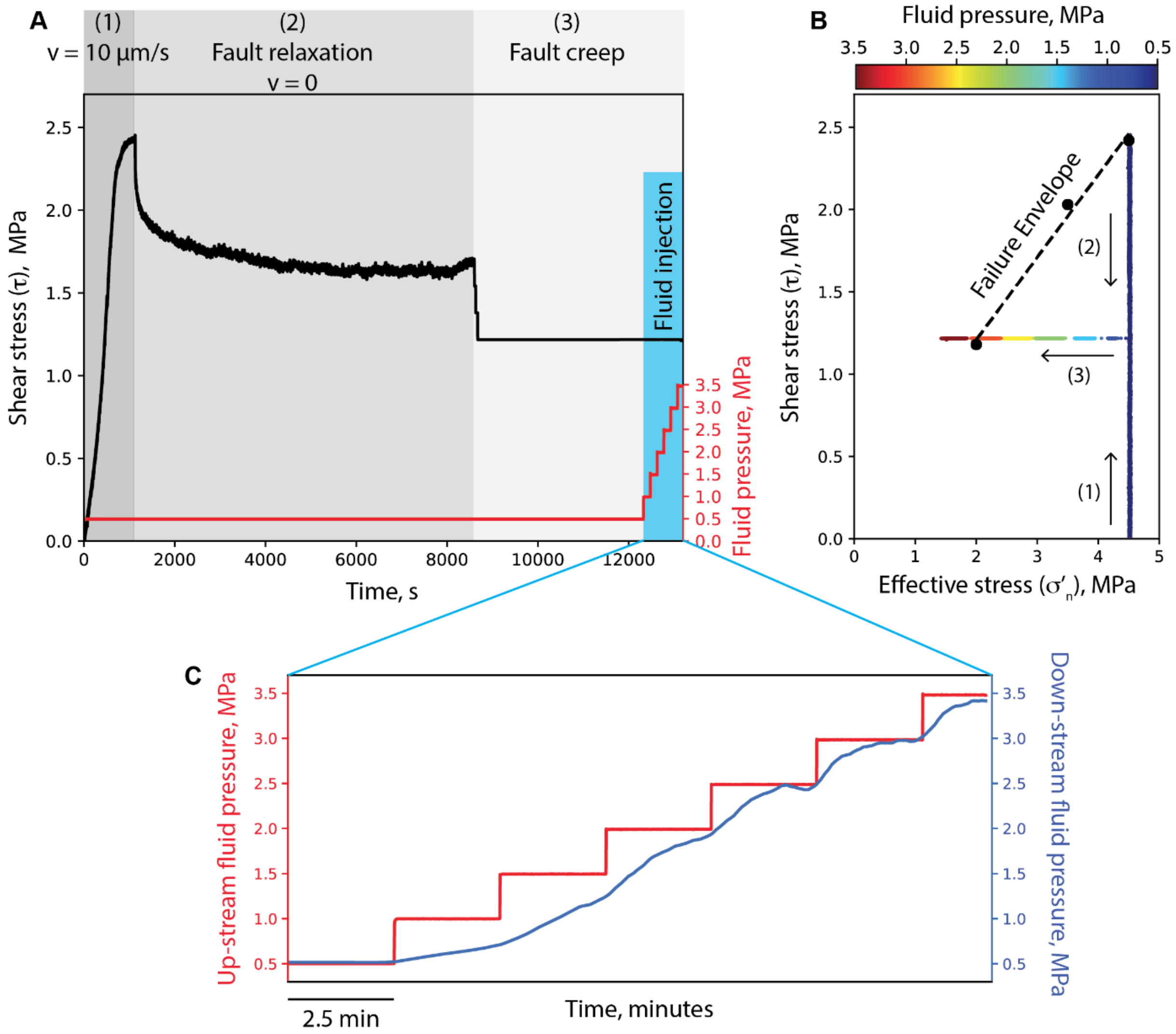

Fig. S2. Experimental procedure during laboratory injection. (**A**) Evolution of shear stress as a function of time. After the first stage at constant displacement rate (1) the fault relaxes (2) and then we fix a constant shear stress at 50% of the steady state shear strength (3). During the creep test, we increase fluid pressure (red curve) step-by-step (0.5 MPa every 150 seconds) and monitor the resulting fault slip and dilation. (**B**) Coulomb failure diagram where we report the experimental data shown in (A). The diagram shows that the experiment represents an extreme pore pressurization relative to the state of stress on the fault. The loading path is indicated with the arrows. Also, reported the failure envelope derived experimentally (each black circle represents the shear strength at steady state derived from a single experiment). (**C**) Close-up view of fluid pressure measured up-stream (red) and down-stream (blue) during injection. The fluid pressure is not in equilibrium at the beginning of injection, while it equilibrates quickly at the end (i.e. during the las third injection steps), that is indicative of an increase of gouge permeability.

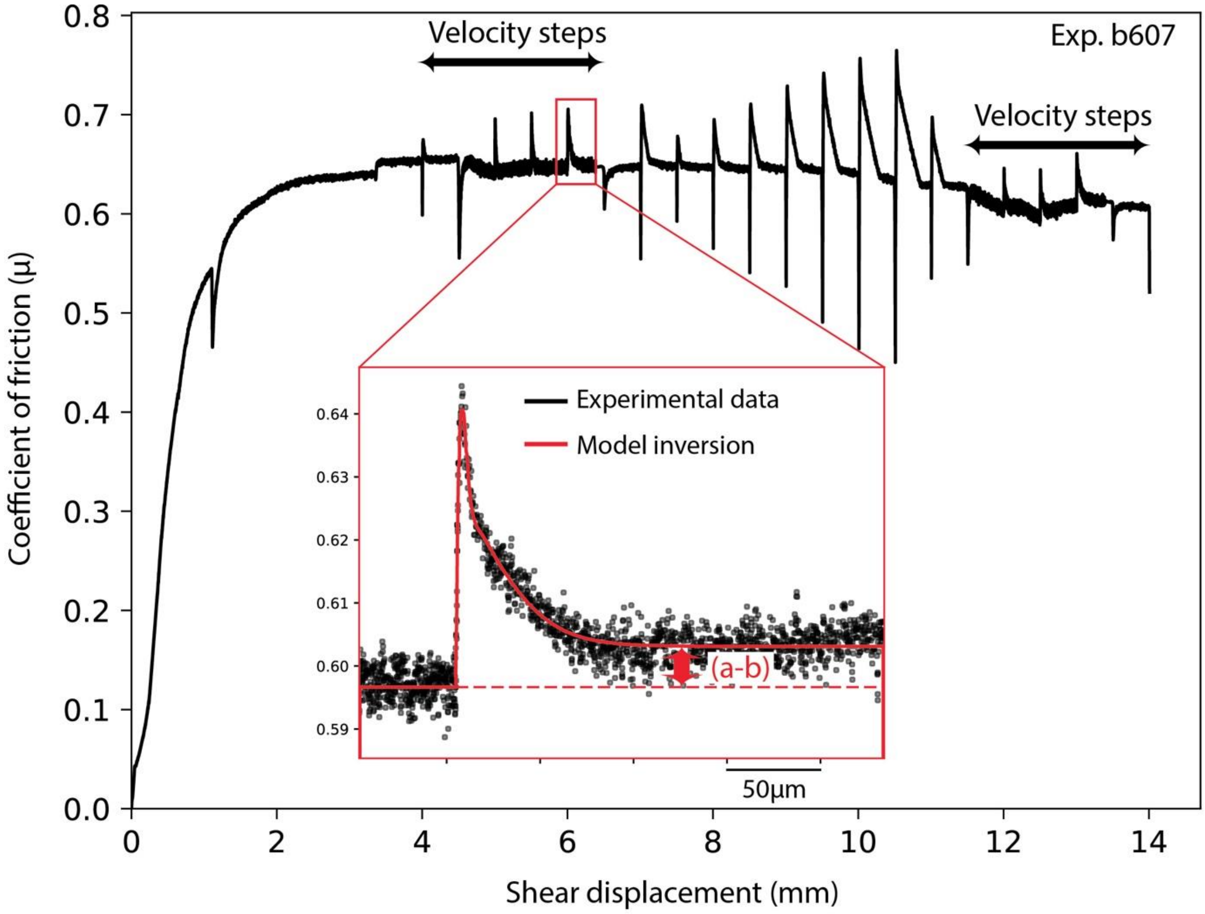

Fig. S3. Representative records (coefficient of friction versus shear displacement) of a velocity-stepping friction experiment with the experimental data (black) and the best-fit solution (red) obtained from the inversion model used to obtain the frictional parameters, resulting in (*a*-*b*) = 0.0013 and d_c = 7.16 µm (see also table S1).

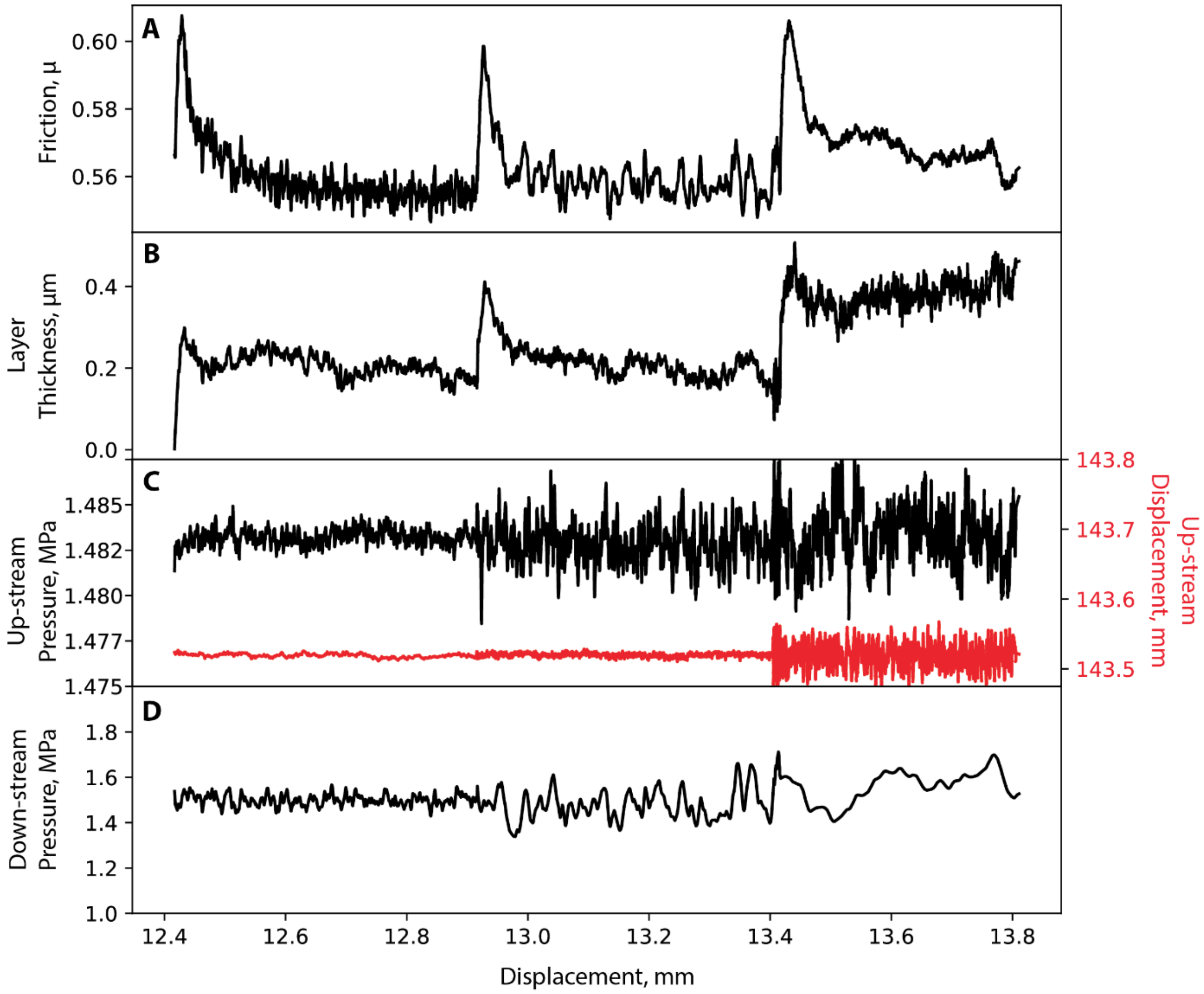

Fig. S4. Frictional response to velocity steps and relationship with fault dilation during a typical fluid pressurized experiment. (**A**) Evolution of the coefficient of friction during velocity step sequence. (**B**) Evolution of the layer thickness after the trend for geometrical thinning has been removed (e.g., 51). (**C**) Evolution of up-stream fluid pressure (black) and up-stream intensifier displacement (red). (**D**) Evolution of down-stream fluid pressure. The data show that during the velocity step sequence the deformation takes place under drained boundary conditions so that the frictional properties measured derive from the rheological properties of the fault gouge and are not related with other mechanisms such as dilation hardening (e.g., 4).

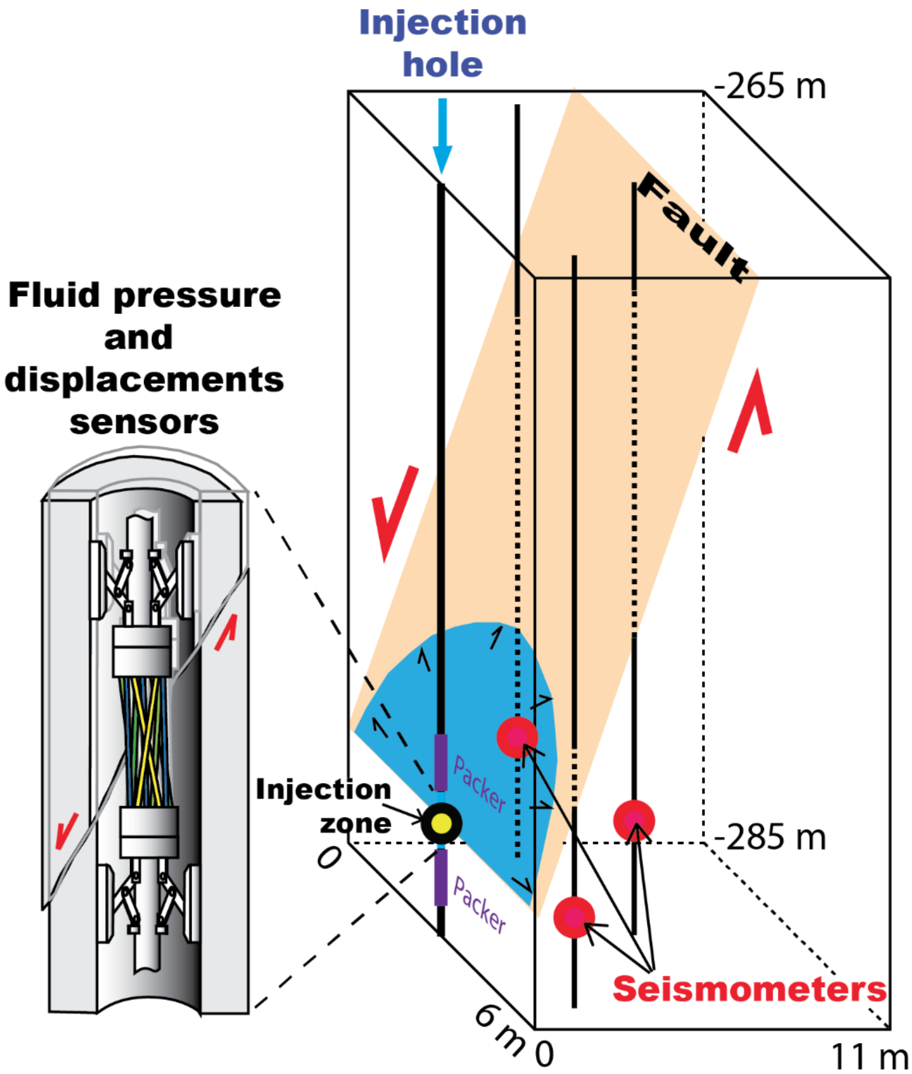

Fig. S5. Experimental conditions of the in situ injection into the natural fault at a depth of 282 m within the LSBB underground laboratory. Fault slip and fluid pressure are measured at the injection site with fiber-optic Bragg sensors installed within the SIMFIP probe (43). Seismometers are installed in the fault and in the surrounding volume. All of them are in boreholes (Modified from 6).

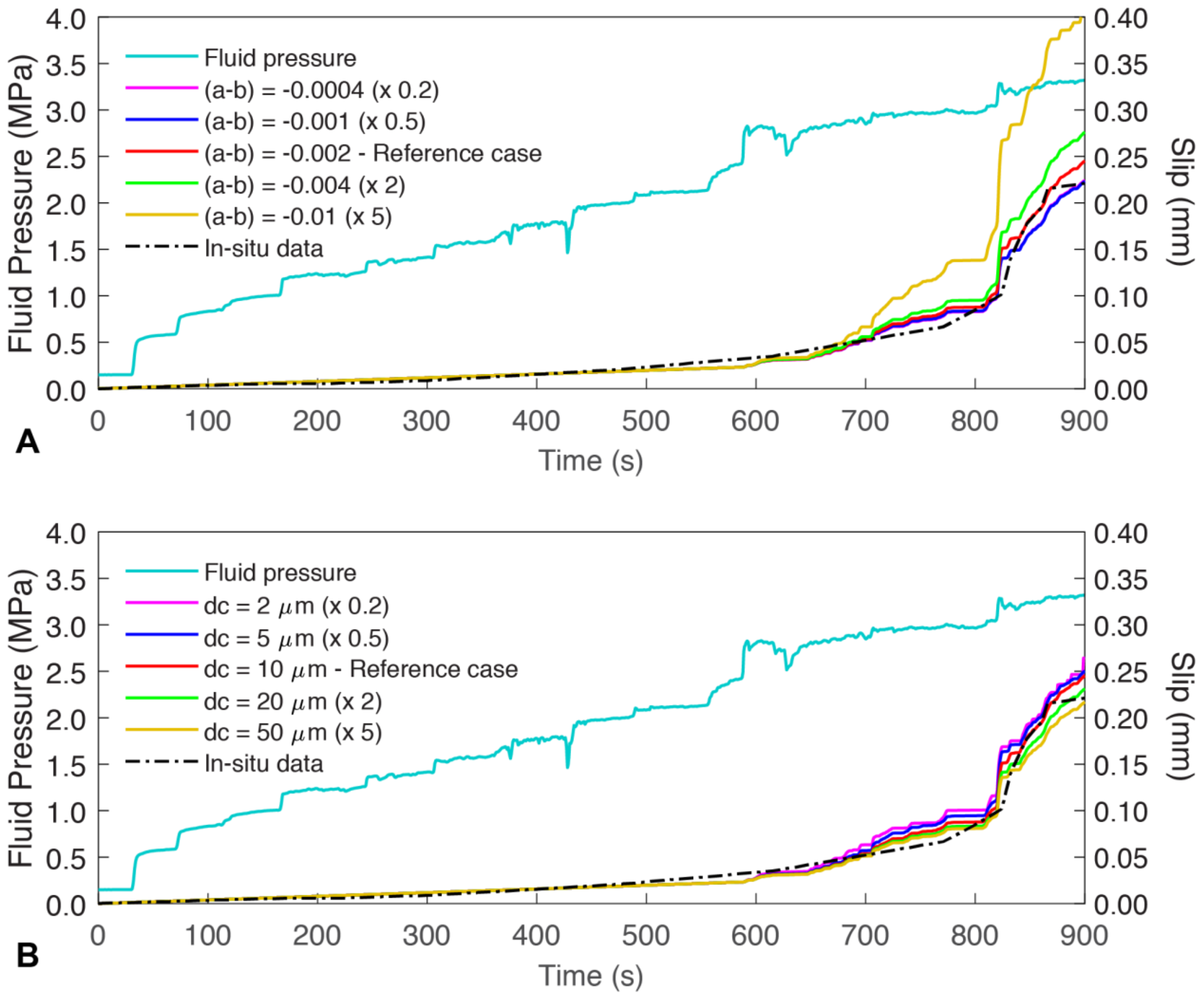

Fig. S6. Sensitivity of the best-fit numerical solution to measurements obtained with a rate-weakening fault model (see Fig. 1C) while varying (A) the parameter (*a*-*b*) and (B) the critical slip distance (d_c). The experimental data are represented by the black dashed line for fault slip, and the light blue solid line for fluid pressure. The best-fitting model parameters (reference case in red) are (*a*-*b*) = -0.002 and d_c = 10 microns.

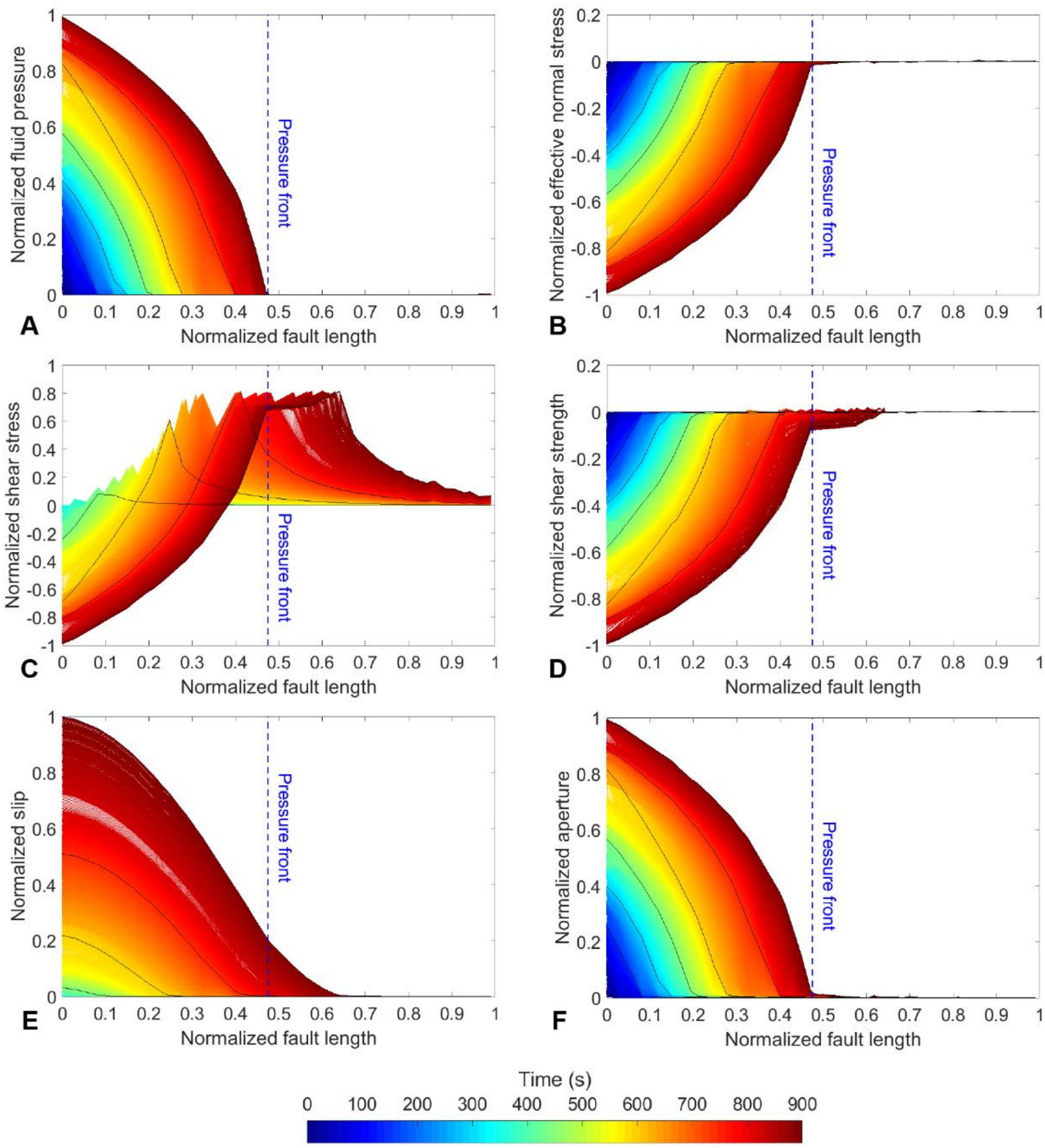

Fig. S7. Model results. Half-profiles of changes in (**A**) fluid pressure, (**B**) effective normal stress, (**C**) shear stress, (**D**) shear strength, (**E**) slip, and (**F**) aperture along the fault. The fluid injection is located at X = 0. All profiles are normalized by their maximum. Thin black lines are plotted every 150 seconds. The location of the fluid pressure front at the end of injection (at 900 seconds) is indicated by the vertical blue dashed line.

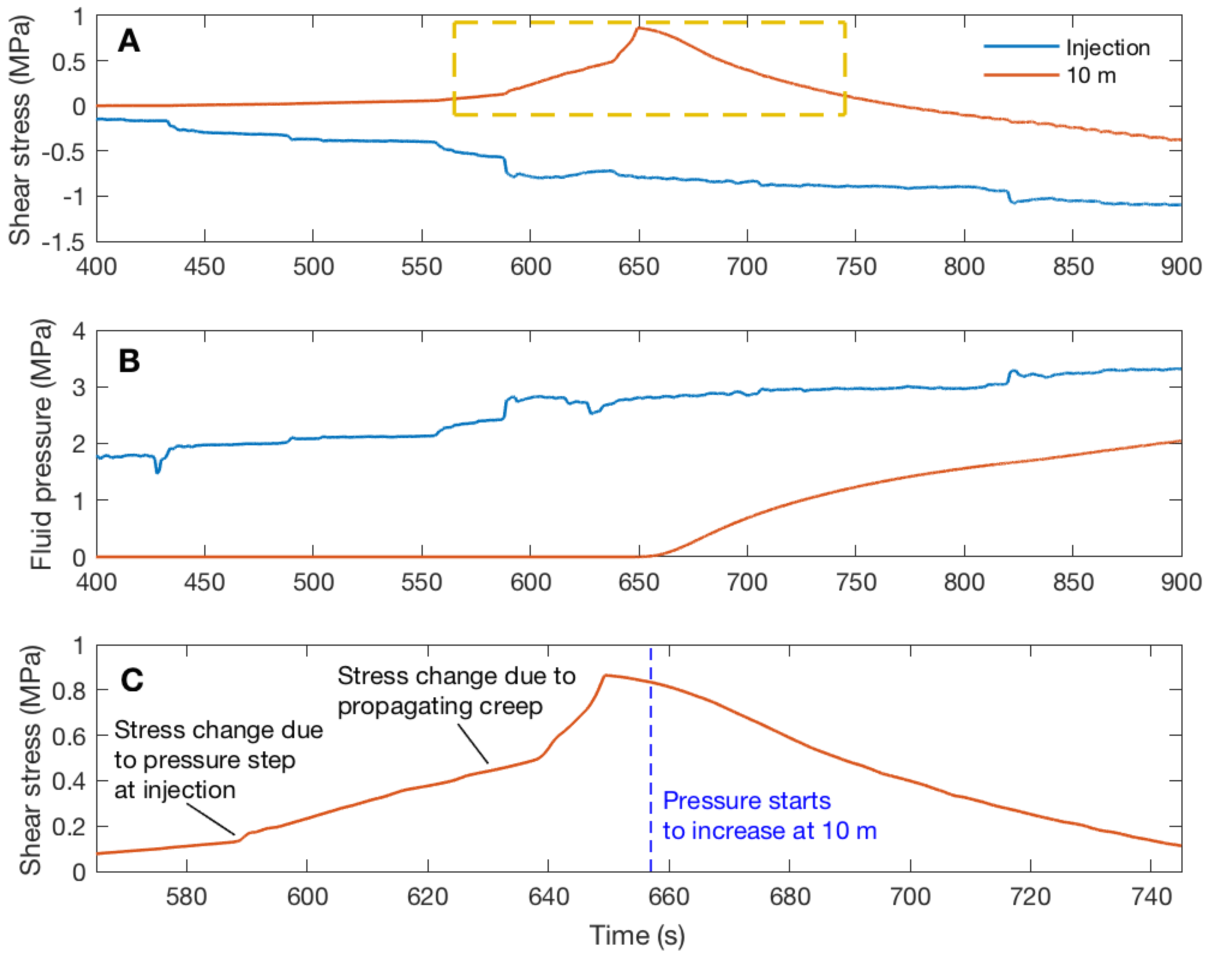

Fig. S8. Model results. (**A**) Changes in shear stress and (**B**) fluid pressure as a function of time at injection (blue) and at a distance of 10 m from the injection (red). (**C**) Zoom into the dashed rectangle (yellow) of the top panel (A) showing static shear stress increase due to the propagating creep beyond the pressure front. The vertical blue dashed line indicates when the pressure starts to increase at a distance of 10 m from the injection.

Table S1. Summary of experiments and boundary conditions used during two series of velocity steps to evaluate frictional parameters (μ_{ss}, μ_o *a-b*, and d_c). We report (Part A) experiment number, normal stress, confining pressure, fluid pressure, effective normal stress, gouge permeability, (Part B) velocity steps and values of frictional parameters. μ_{ss} is the steady state friction before each velocity step. μ_o is the friction coefficient taken at a reference slip velocity of 10 microns per second for each effective stress.

Part A

Experiment number	Normal stress (MPa)	Confining pressure (MPa)	Fluid pressure (MPa)	Effective stress (MPa)	Steady-state friction coefficient (μ_{ss})	Permeability (m^2)
B607	5	0	Saturated $P_f = 0$		0.63	
B609	5	0	Dry		0.63	
B608	1	4	3	2	0.57	4.2×10^{-17}
B633	1	4	1.5	3.5	0.57	1.1×10^{-16}

Part B

Experiment number	Velocity steps (μm/s)	First series of velocity steps			Second series of velocity steps		
		(a-b)	d_c (μm)	μ_o	*(a-b)*	d_c (μm)	μ_o
B607	10-0.1	-0.00031	44.358	0.65	0.00013	26.651	0.62
	0.1-1	0.0013	7.1650	0.64	0.00063	19.455	0.60
	1-10	-0.00019	10.901	0.64	0.0028	17.635	0.59
	10-100	0.0015	20.876	0.64	0.0020	59.602	0.60
B609	10-0.1	0.00093	12.664	0.63	-0.0020	12.022	0.57
	0.1-1	0.00024	1.2038	0.60	-0.0021	2.0885	0.57
	1-10	-0.00039	5.8259	0.61	-0.0011	5.0102	0.56
	10-100	0.0014	9.6808	0.61	-0.0009	11.079	0.56
B608	10-0.1	-0.010	79.170	0.59			
	0.1-1	-0.0038	9.4536	0.57			
	1-10	0.0013	10.603	0.56			
	10-100	0.0056	17.848	0.58			
B633	10-0.1	-0.0034	55.912	0.57			
	0.1-1	-0.0017	46.955	0.56			
	1-10	0.0024	23.044	0.55			
	10-100	0.0018	32.329	0.56			

Table S2. Summary of boundary conditions during the creep experiment. We report experiment number, normal stress, confining pressure, fluid pressure, effective normal stress, value of injection rate, and friction coefficient (μ_o) before injection.

Experiment number	Normal stress (MPa)	Confining pressure (MPa)	Fluid pressure (MPa)	Effective stress (MPa)	Injection rate	Friction coefficient (μ_o)
B632	1	4	0.5 to 3.5	4.5 to 1.5	0.5 MPa / 2.5 minutes	0.53